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Solar neutrinos, θ_{13} and non-standard ν properties

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Excellence Cluster 'Universe'

Outline

- Introduction
- A weak tension in the solar sector
- The official medicine: Standard kinematics (θ_{13}>0)
- The alternative cure: Non-standard dynamics (NSI)
- Conclusions

Introduction

The leptonic mixing

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i} |\nu_i\rangle$$

$(i = 1, 2, 3)$

$(\alpha = e, \mu, \tau)$

$$U = O_{23}\Gamma_\delta O_{13}\Gamma^\dagger_\delta O_{12}$$

$\Gamma_\delta = \mathrm{diag}(1, 1, e^{+i\delta})$

$\delta \in [0, 2\pi]$ Dirac CP-violating phase

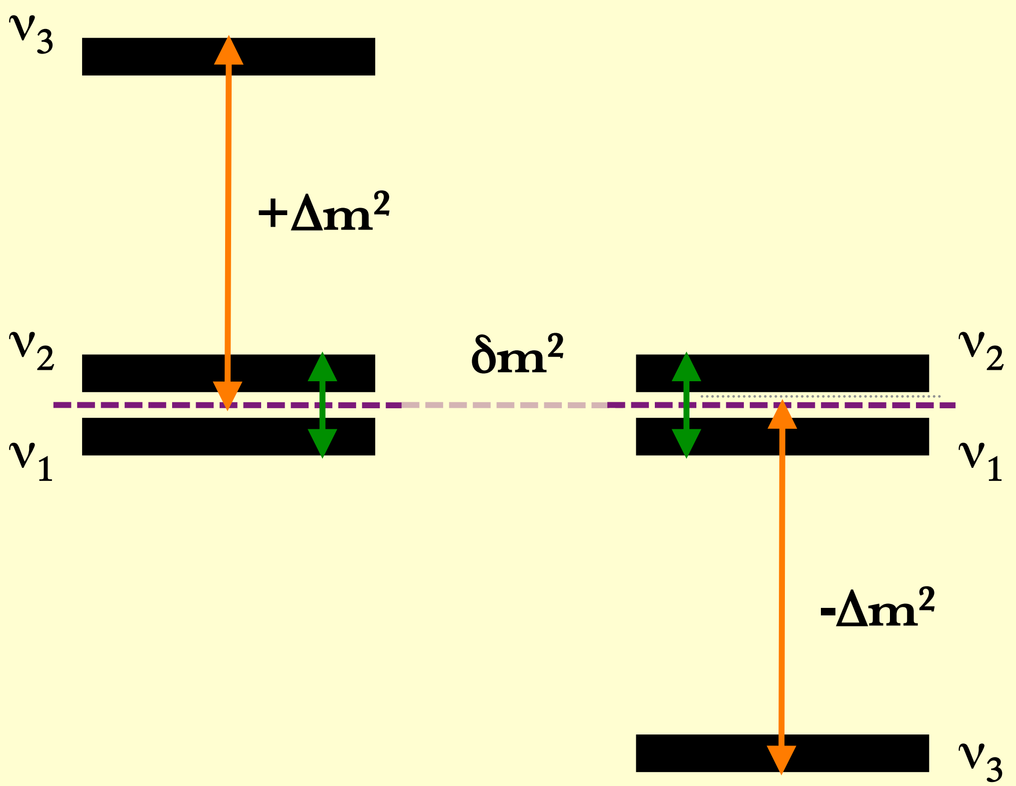
unknown

Explicit form:

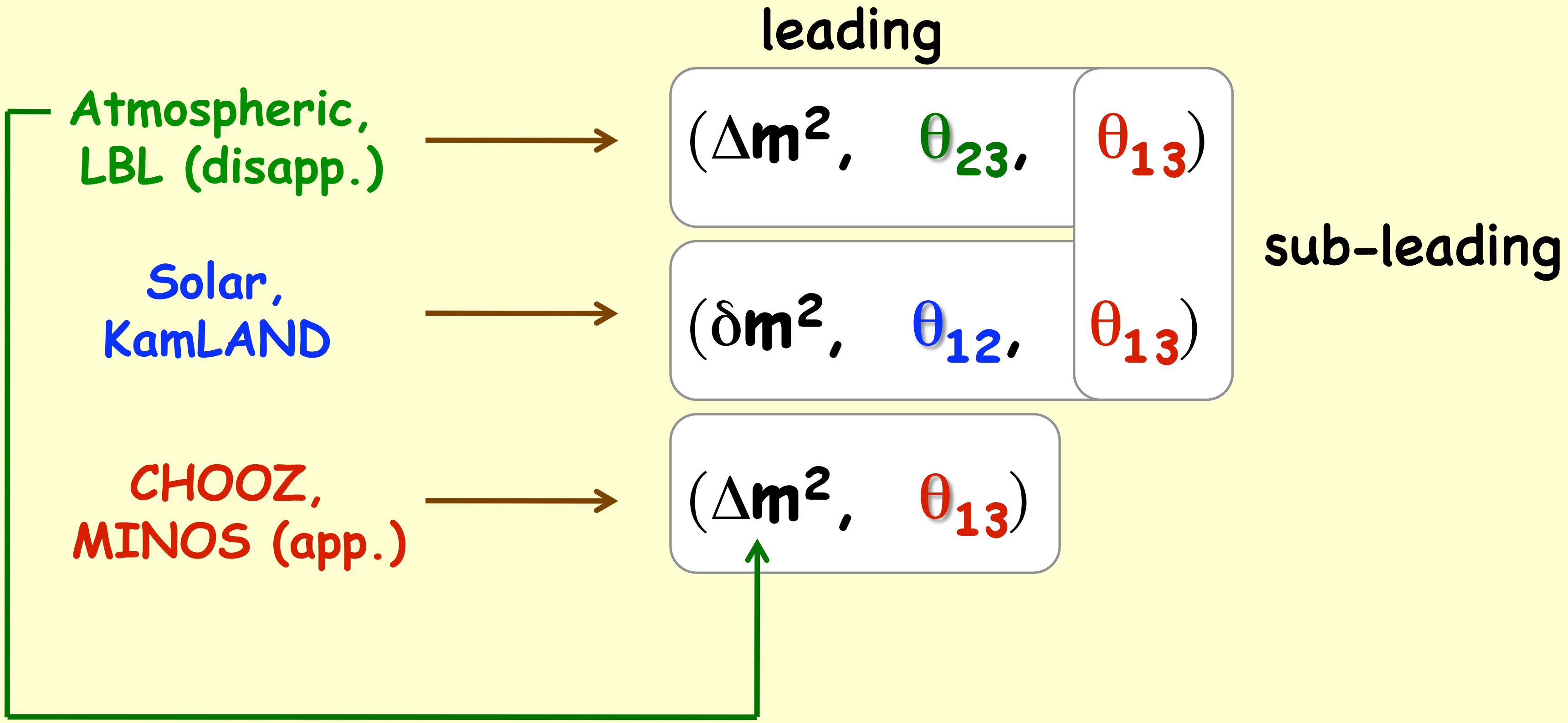
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

The neutrino mass spectrum

NH IH ?



Experimental Sensitivities



leading

sub-leading

Atmospheric, LBL (disapp.) → $(\Delta m^2, \ \theta_{23}, \ \theta_{13})$

Solar, KamLAND → $(\delta m^2, \ \theta_{12}, \ \theta_{13})$

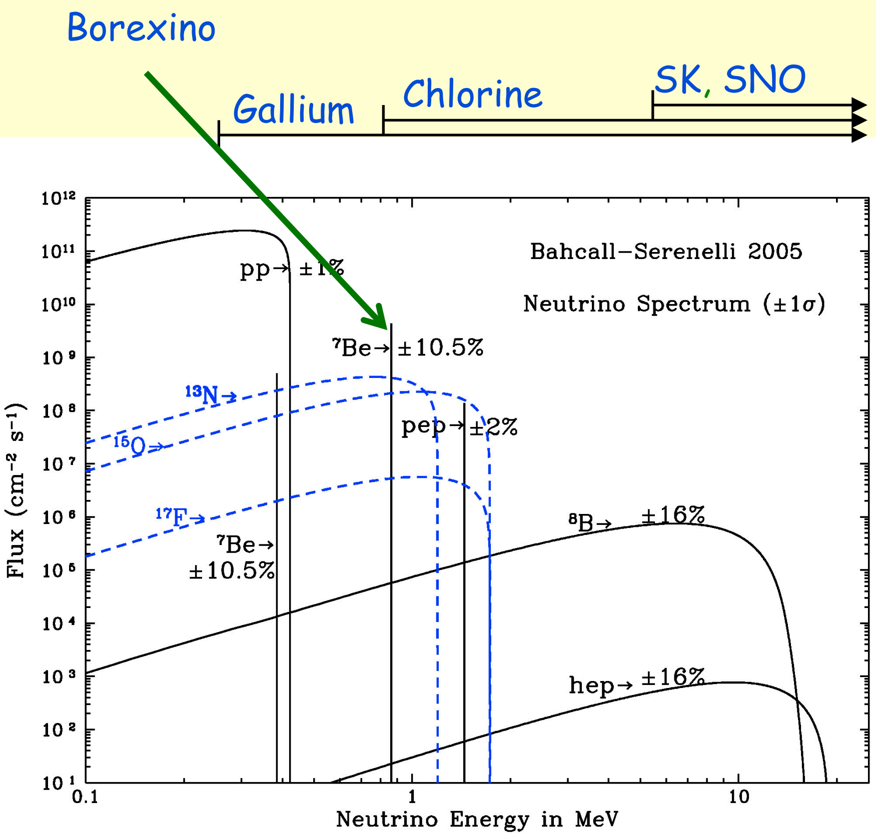
CHOOZ, MINOS (app.) → $(\Delta m^2, \ \theta_{13})$

Solar neutrinos

neutrino fluxes …

BS(05) OP

	Source	Reaction	Energy (MeV)	Flux (cm^{-2}s^{-1})
pp	**pp**	p+p$\rightarrow$ ^{2}H+e^++ν_e	$\leq$ 0.42	5.99×10^{10}
	pep	p+p+e^- $\rightarrow$ ^{2}H+ν_e	1.44	1.42×10^{8}
	B	^{8}B$\rightarrow$ ^{8}Be+e^++ν_e	$\leq$ 15	5.69×10^{6}
	hep	^{3}He+p$\rightarrow$ ^{4}He+e^++ν_e	$\leq$ 18.77	7.93×10^{3}
	Be^1	^{7}Be+e^- $\rightarrow$ ^{7}Li+ν_e	0.38 (10.3%)	0.68×10^{9}
	Be^2	(2nd branch)	0.86 (89.7%)	4.16×10^{9}
CNO	N	^{13}N$\rightarrow$ ^{13}C+e^++ν_e	$\leq$ 1.20	3.07×10^{8}
	O	^{15}O$\rightarrow$ ^{15}N+e^++ν_e	$\leq$ 1.73	2.33×10^{8}
	F	^{17}F$\rightarrow$ ^{17}O+e^++ν_e	$\leq$ 1.74	5.84×10^{6}



… and their energy spectra

The solar neutrino experiments

Radiochemical

Homestake ($E_\nu > 0.818$ MeV)

$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$

SAGE & GALLEX-GNO ($E_\nu > 0.232$ MeV)

can see pp

$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$

Real time

SK (High E)

ES: $\nu_x + e^- \rightarrow \nu_x + e^-$

Borexino (Low & High E)

ES: $\nu_x + e^- \rightarrow \nu_x + e^-$

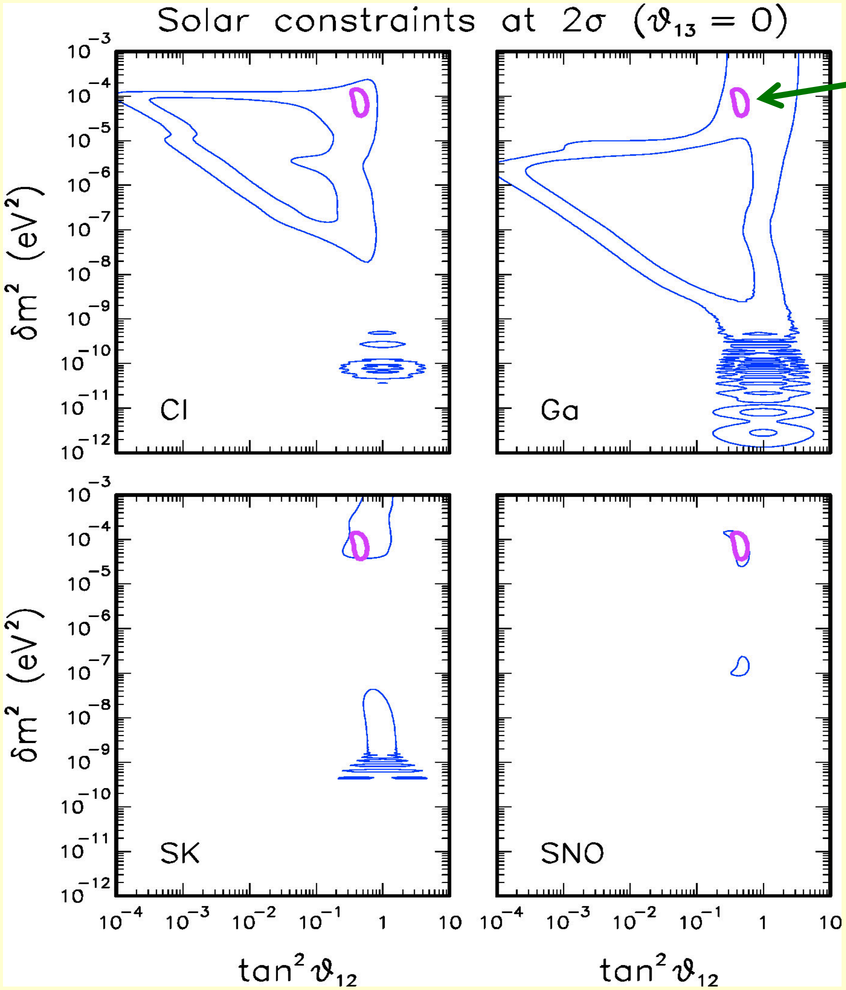
SNO ($E > 5$ MeV)

CC: $\nu_e + d \rightarrow p + p + e^-$

flavor blind → **NC:** $\nu_x + d \rightarrow p + n + \nu_x$

ES: $\nu_x + e^- \rightarrow \nu_x + e^-$

Solar ν data single out a unique solution

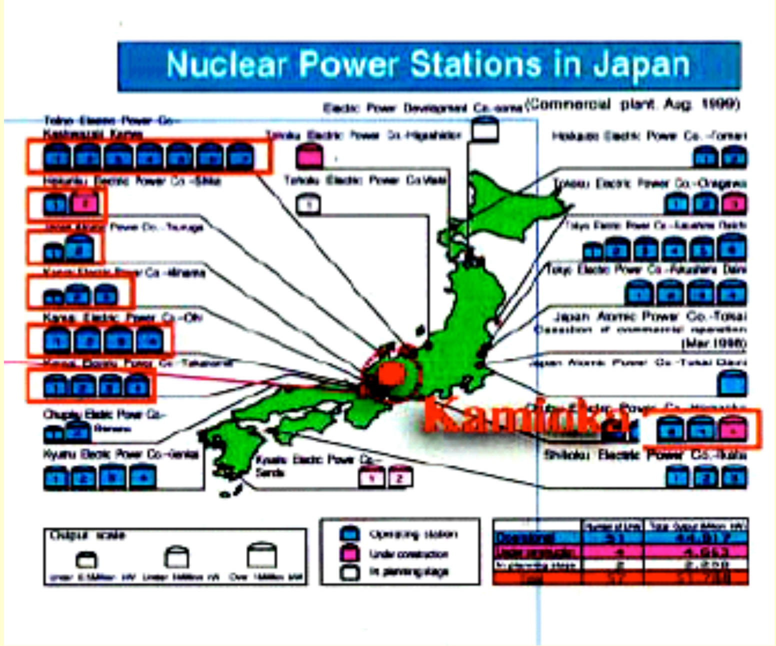


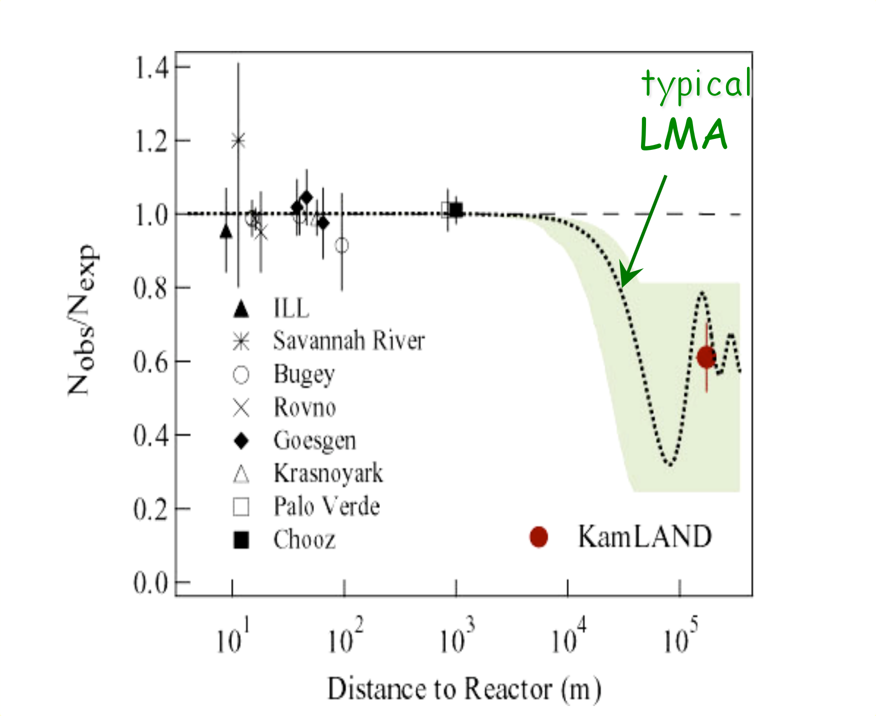
"LMA"

Non trivial **consistency**
among different experiments

Fit dominated by **high-E** data
and in particular by **SNO**

KamLAND: long-baseline multi-reactor experiment





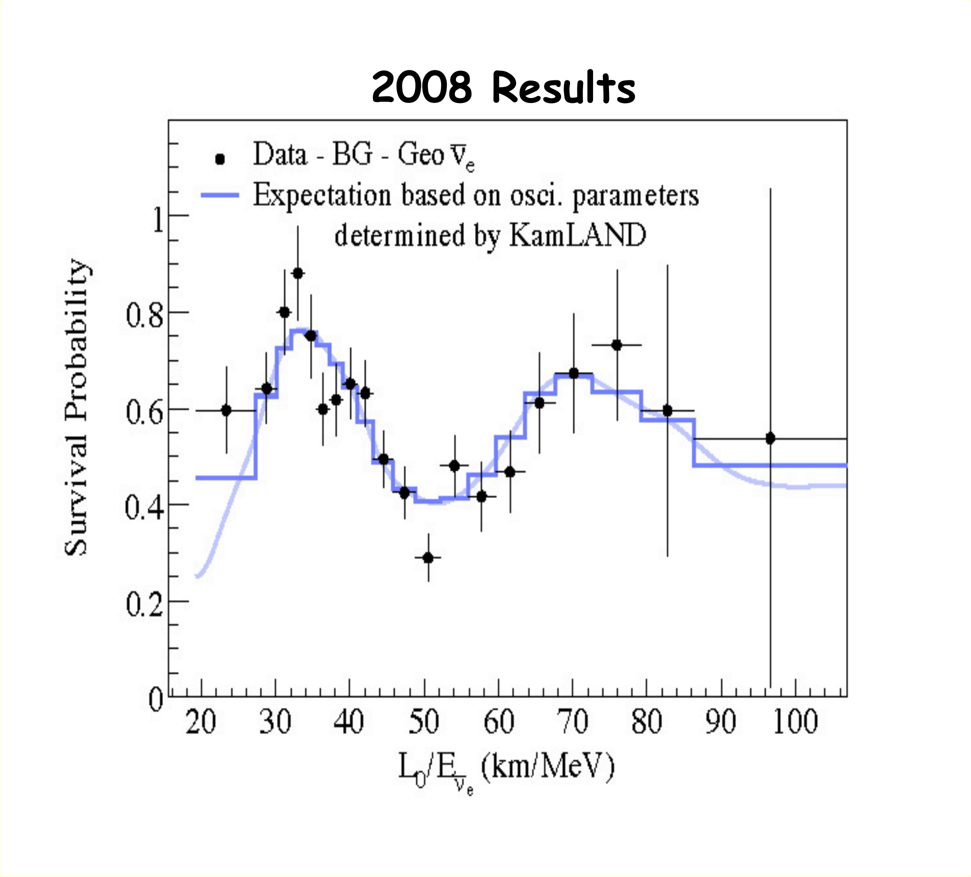
typical LMA

Average distance: ~180 km

Typical ν energy: few MeV

Sensitivity to δm^2 ~ few x 10^{-5} eV^2

Spectacular confirmation of oscillations

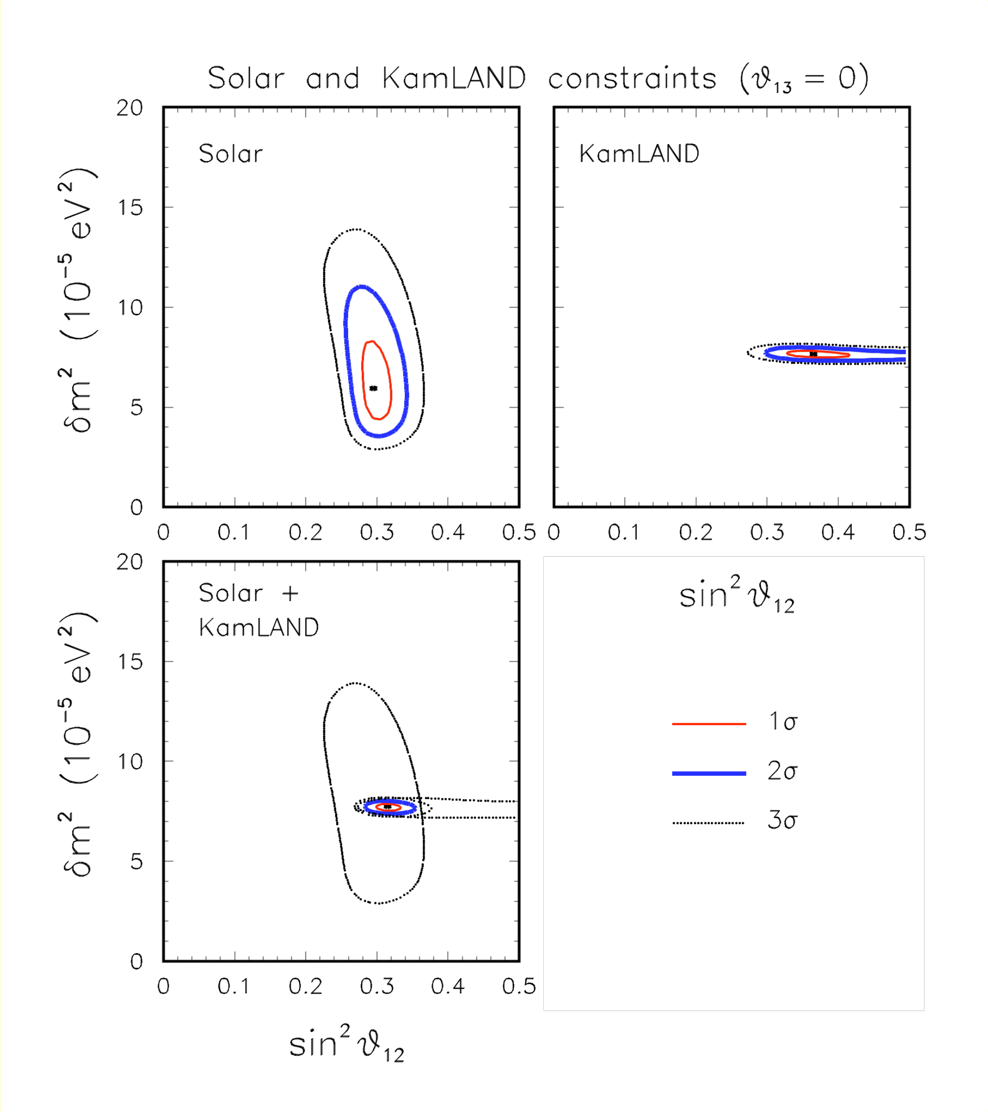

2008 Results

Precision measurement of spectral distortions

Osc. pattern observed over one entire cycle

Determination of δm^2 with high precision

2ν Solar + KamLAND constraints

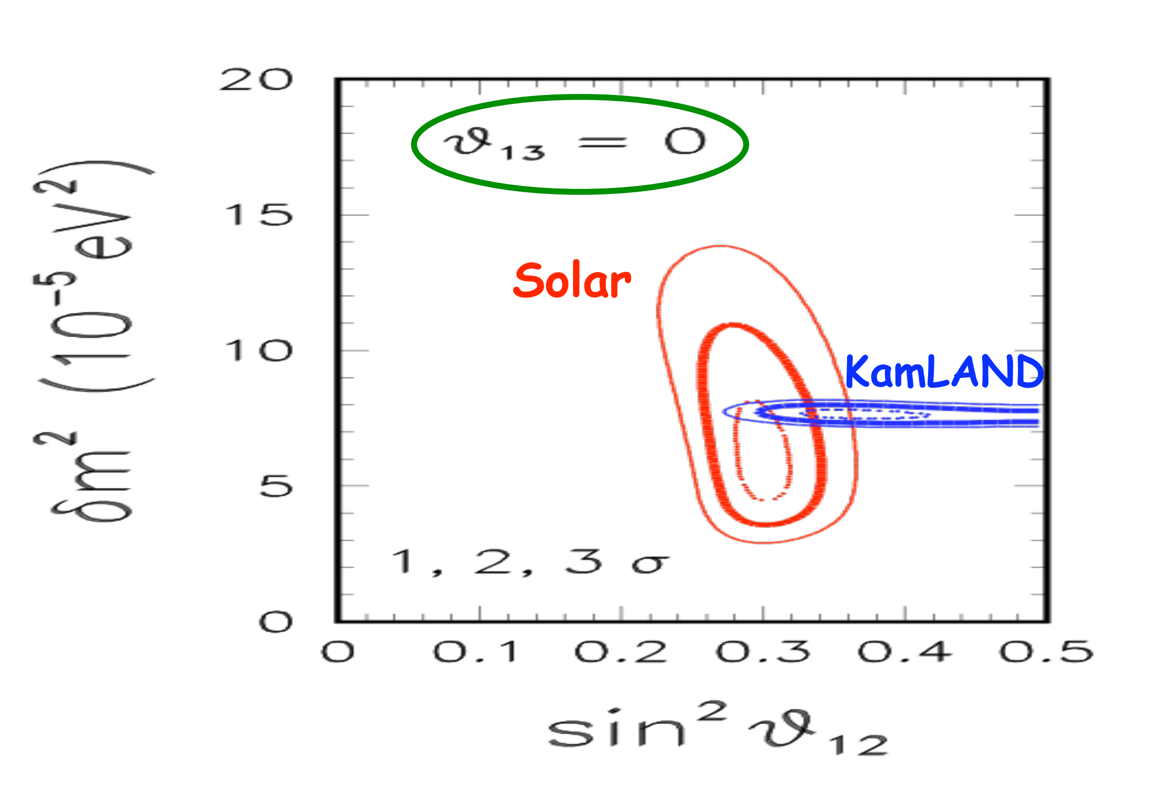


KamLAND dominates δm^2 determination

Interplay of Solar and KamLAND in determining θ_{12}

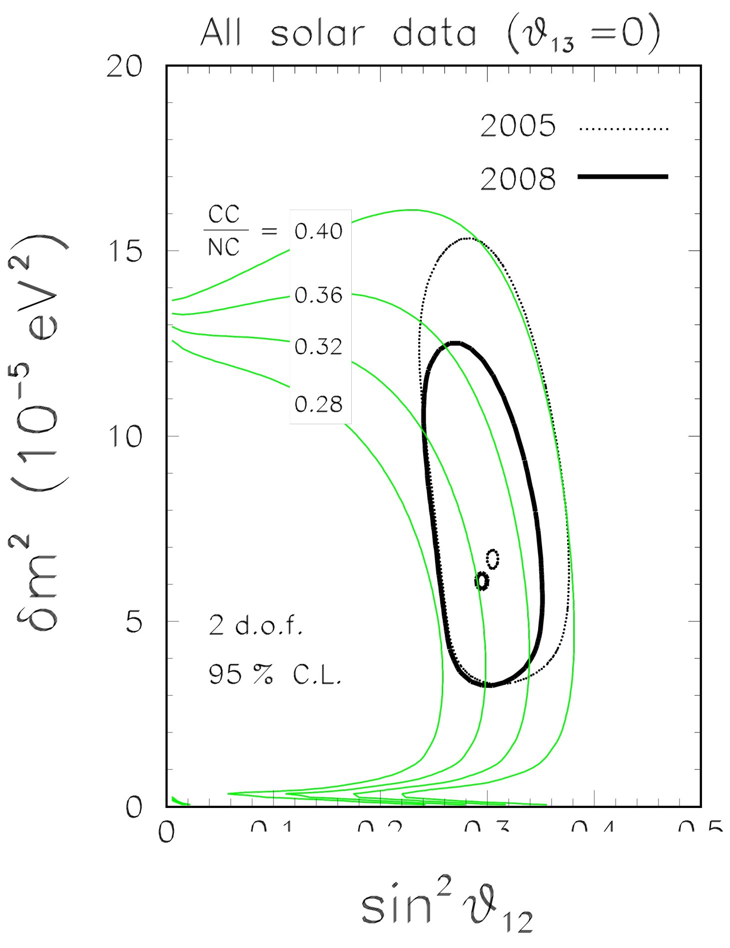
But small tension among them is present…

A weak tension in the solar sector



Do we need to bother with it?

What lies behind the S-K tension



	2005 SNO-II	2008 SNO-III
$\frac{CC}{NC}$ =	0.340 ± 0.038	0.301 ± 0.033

- **Central value lower than before**

best fit of θ_{12} at a
slightly lower value

- **Error reduced when combined**

range allowed for θ_{12}
appreciably narrowed

- **Apparently a small change**

but big enough to give
rise to a significant
tension with KamLAND

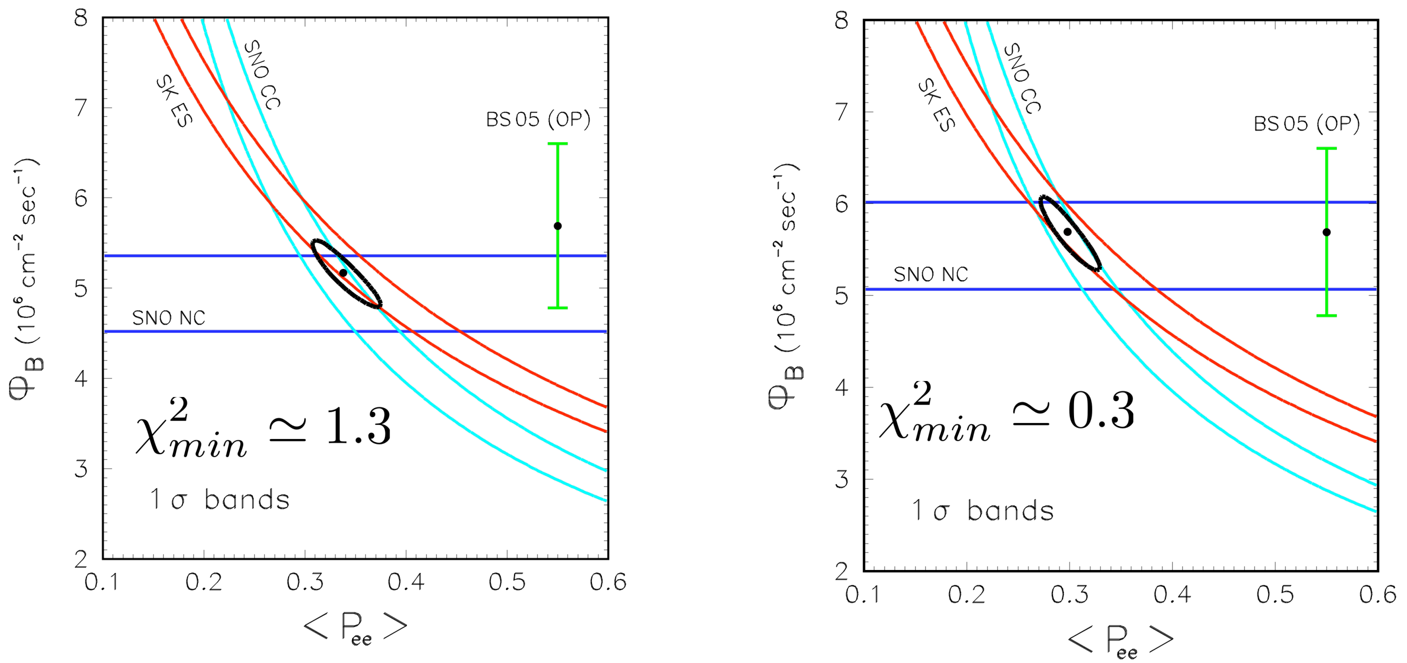
SNO III: just a statistical fluctuation?

1) **“Internal” consistency among SNO** (CC,NC) **and SK** (ES)

2) **Consistency among NC and Solar Model**

both already good …and… now excellent

SNO-II (2005) **SNO-III (2008)**



Maybe not!

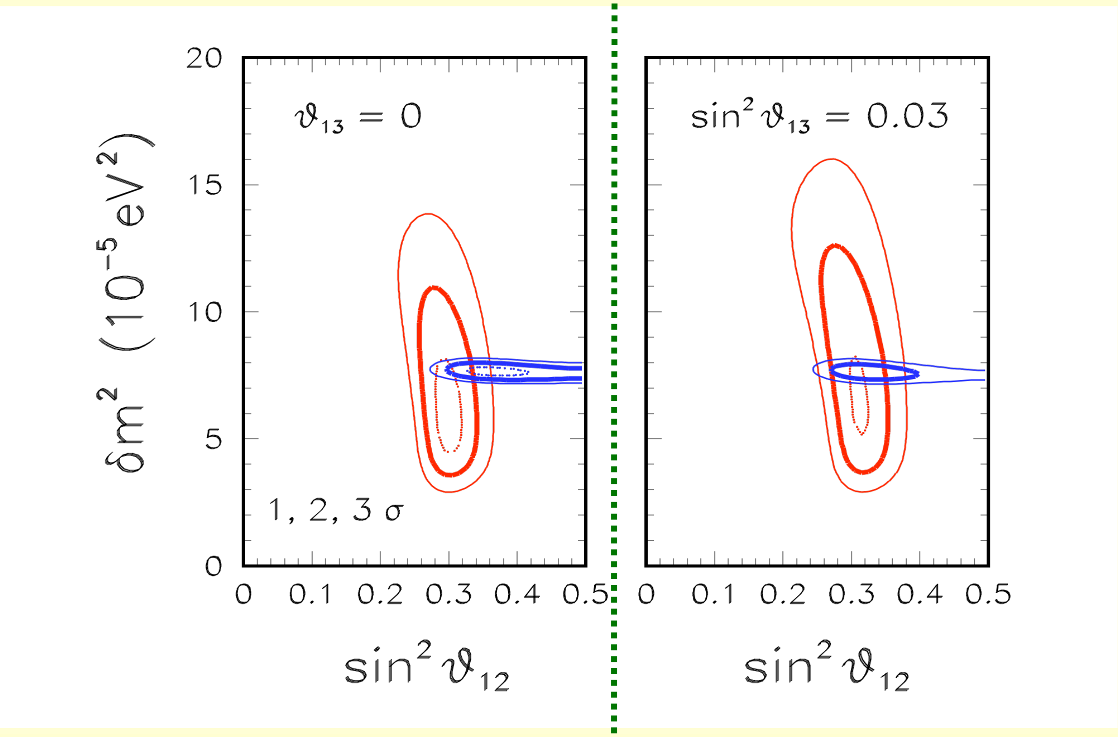
How can we cure the S-K tension ?

The standard remedy

Perturbing the kinematics: non-zero θ_{13}

θ_{13} reduces the S-K disagreement

$\theta_{13} = 0$



$\theta_{13} > 0$

For $\theta_{13} = 0$
Solar and KamLAND
prefer different values of θ_{12}
No overlap at 1σ level

For $\theta_{13} > 0$
Solar data prefer higher θ_{12}
KamLAND prefers lower θ_{12}
Disagreement reduced*

*See also Balantekin and Yilmaz, J. Phys. G. 35, 075007 (2008)

To understand the S-K interplay it is helpful to look first at the solar ν 2-flavor survival probability

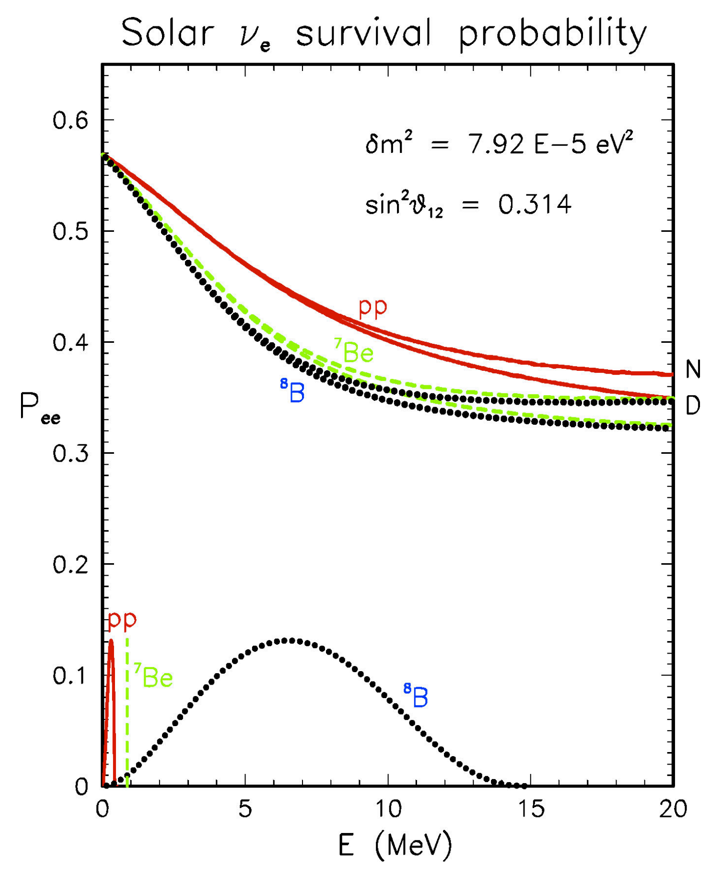
Low-E

"vacuum-like"
regime

$P_{ee} \sim$
$1 - \frac{1}{2}\sin^2 2\theta_{12}$

Gallium,
Borexino

low
sensitivity



High-E

"matter-enhanced"
regime

$P_{ee} \sim \sin^2 \theta_{12}$

Cl, SK, SNO
Borexino

dominate
in the global fit

3-flavor perturbations

$$\mathrm{P}_{ee}^{3\nu} \simeq s_{13}^4 + c_{13}^4 P_{ee}^{2\nu}$$

$$\Delta m^2 \to \infty$$

one-mass-scale approximation

For small values of θ_{13} : Pee suppression

High-E solar ⟶

$$P_{ee} \simeq (1 - 2s_{13}^2)(+ s_{12}^2)$$

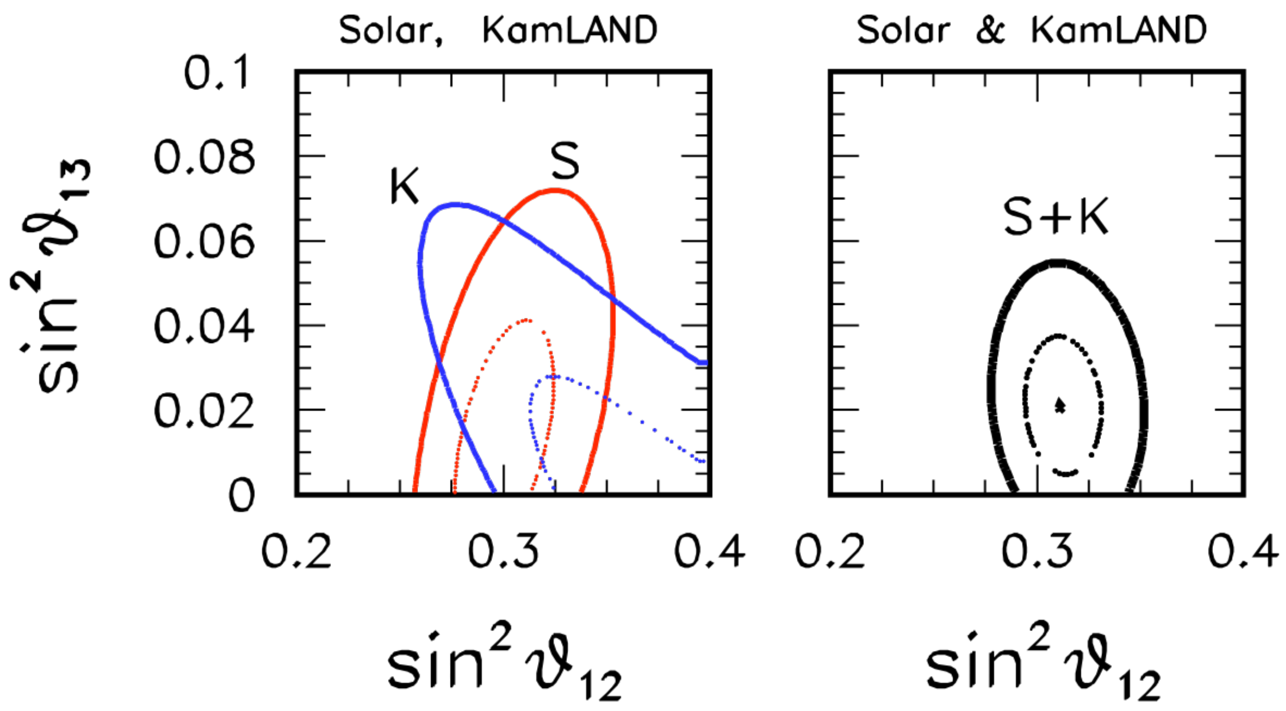
KamLAND (~vacuum) ⟶

$$P_{ee} \simeq (1 - 2s_{13}^2)(1 - 4s_{12}^2 c_{12}^2 \sin^2 \phi)$$

$$\phi = \frac{\delta m^2 L}{4E}$$ oscillation phase

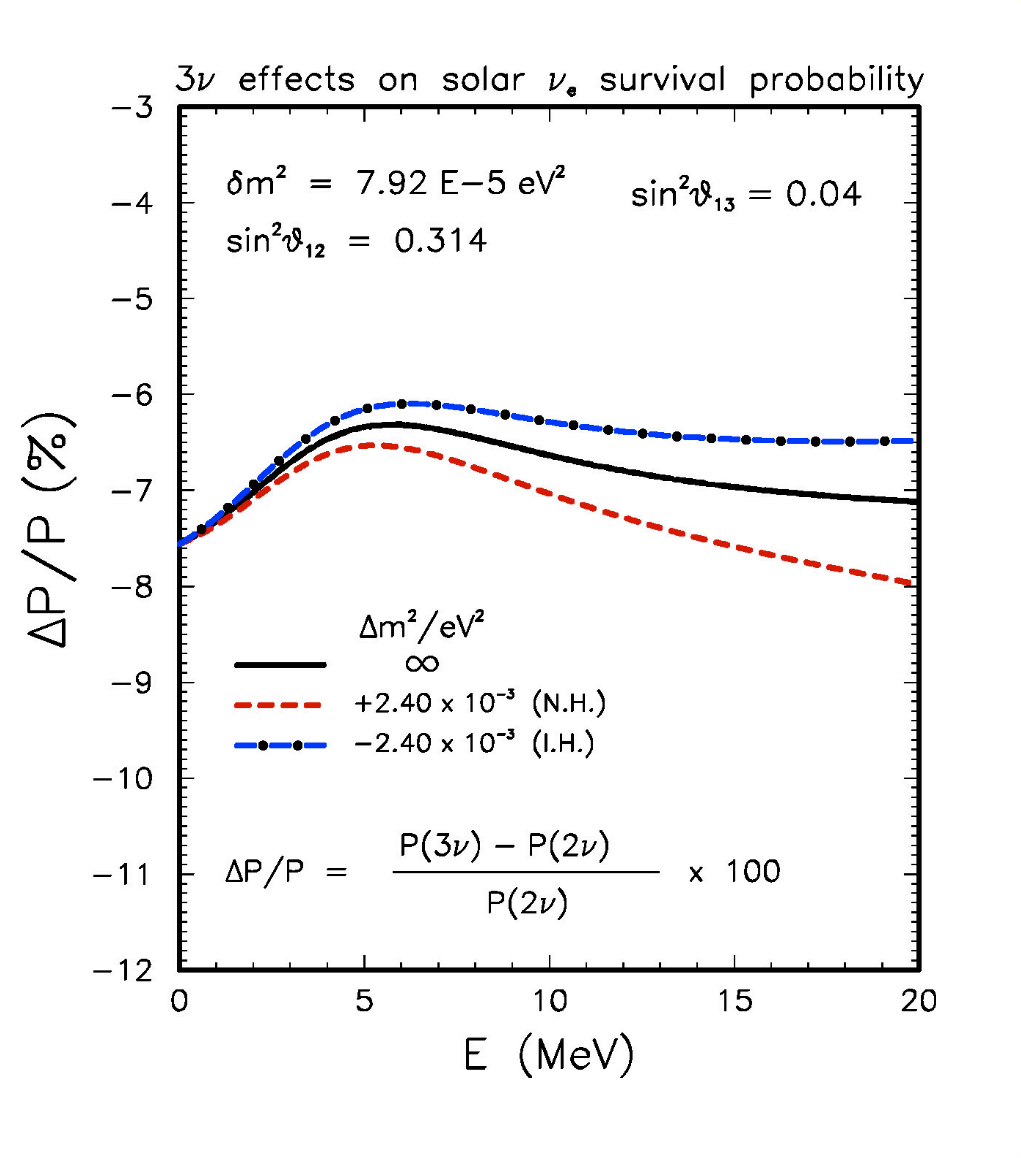
Different relative sign for (θ_{12}, θ_{13}) in P_{ee}

Different [θ_{12}, θ_{13}] correlation in solar (S) and KamLAND (K)



G.L Fogli, E. Lisi, A. Marrone, A.P., A.M. Rotunno
arXiv:0806.2649 [hep-ph], PRL 101, 141801 (2008

θ_{13} does not affect appreciably the dynamics



$(V \to V c_{13}^2)$

MSW dynamics is almost unchanged

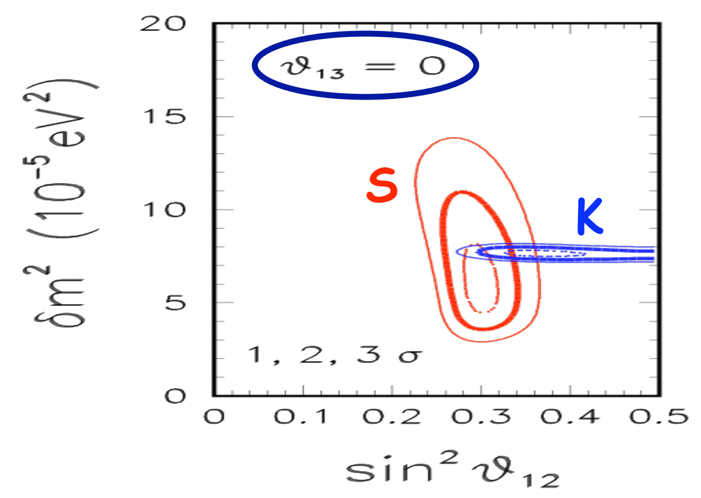
non-zero θ_{13} induces only a mild energy dependence

main effect is the kinematical one (Energy indep. Pee suppression)

The alternative cure

Perturbing the dynamics: non-standard interactions (NSI)

A matter-vacuum tension ?



The S-K tension can be seen as a disagreement between the (standard) interpretation of flavor transitions occurring <u>in two different conditions</u>:

Solar ν's:

matter-enhanced

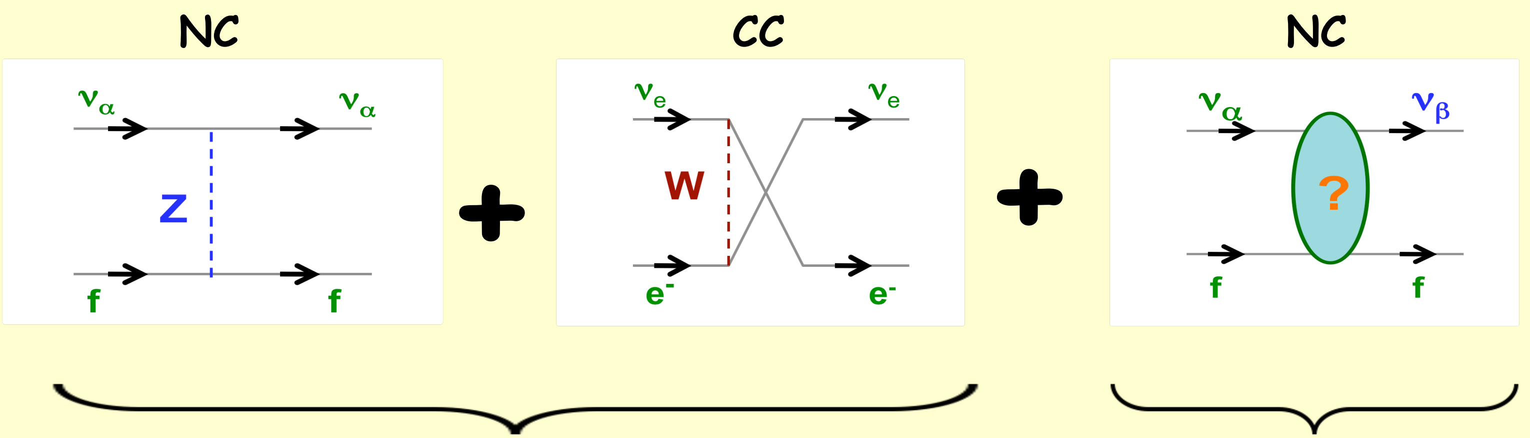
KamLAND ν's:

~vacuum

From this perspective, it is meaningful to hypothesize that the tension may result from some <u>unaccounted</u> effect intervening in the dynamics of solar ν transitions.

Non-standard interactions (NSI) offer one such possibility, as they can alter the coherent forward scattering of solar ν's on the constituents of the ordinary matter (Wolfestein 1978).

Coherent forward scattering in the presence of NSI : Pictorial view



Standard interaction terms

NSI term(s)

NSI described by an effective four-fermions operator

$$O^{\mathrm{NSI}}_{\alpha\beta} \sim \overline{\nu}_\alpha \nu_\beta \overline{f} f$$

$(\alpha, \beta) = e, \mu, \tau$

$f \equiv (e, u, d)$

Coherent forward scattering in the presence of NSI : Math. view

Evolution in the flavor basis:

$$i\,\frac{d}{dx}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = H\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

H contains three terms:

$$H = H_{\rm kin} + H^{\rm std}_{\rm dyn} + H^{\rm NSI}_{\rm dyn}$$

Kinematics

$$H_{\rm kin} = U\begin{pmatrix}-\delta k/2 & 0 & 0\\ 0 & +\delta k/2 & 0\\ 0 & 0 & k/2\end{pmatrix}U^\dagger$$

$$\delta k = \delta m^2/2E$$

$$k = m^2/2E$$

Standard MSW dynamics

$$H^{\rm std}_{\rm dyn} = {\rm diag}(V,\,0,\,0)$$

$$V(x) = \sqrt{2}G_F N_e(x)$$

Non-standard dynamics

$$(H^{\rm NSI}_{\rm dyn})_{\alpha\beta} = \sqrt{2}\,G_F\,N_f(x)\epsilon_{\alpha\beta}$$

Reduction to an effective two flavor dynamics

One mass scale approximation: $\Delta m^2 \rightarrow \infty$

$$P_{ee} = c_{13}^4 P_{ee}^{\rm eff} + s_{13}^4$$

survival probability

$$i\,\frac{d}{dx}\left(\begin{array}{c}\nu_e\\ \nu_a\end{array}\right) = H^{\rm eff}\left(\begin{array}{c}\nu_e\\ \nu_a\end{array}\right)$$

effective evolution

$$H^{\rm eff} = V(x)\begin{pmatrix} c_{13}^2 & 0\\ 0 & 0\end{pmatrix} + \sqrt{2}G_f N_d(x)\begin{pmatrix} 0 & \varepsilon\\ \varepsilon & \varepsilon'\end{pmatrix}$$

d-quark

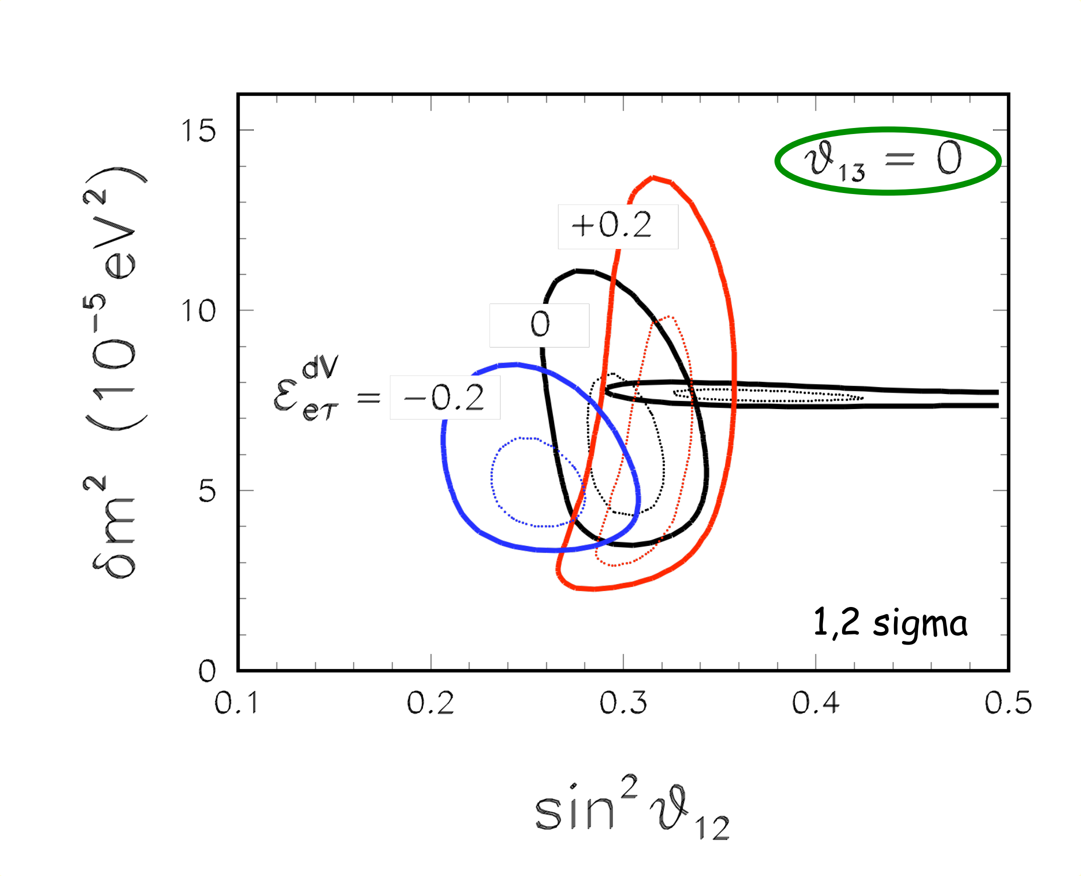
$$\varepsilon = -\varepsilon_{e\tau} c_{13} s_{23}$$

$$\varepsilon' = +2\varepsilon_{e\tau} s_{13} c_{13} c_{23}$$

for ν_e <-> ν_τ FCNC

Parameter space: $[\delta m^2, \theta_{12}, \theta_{13}, \theta_{23}, \varepsilon_{e\tau}]$

Impact of NSI on solar LMA



A. P. and J.W.F. Valle, PRD 80, 091301 (R) (2009)
arXiv:0909.1535 [hep-ph]

Positive values of ε shift the LMA towards bigger values of θ_{12}

alleviating the tension with KamLAND

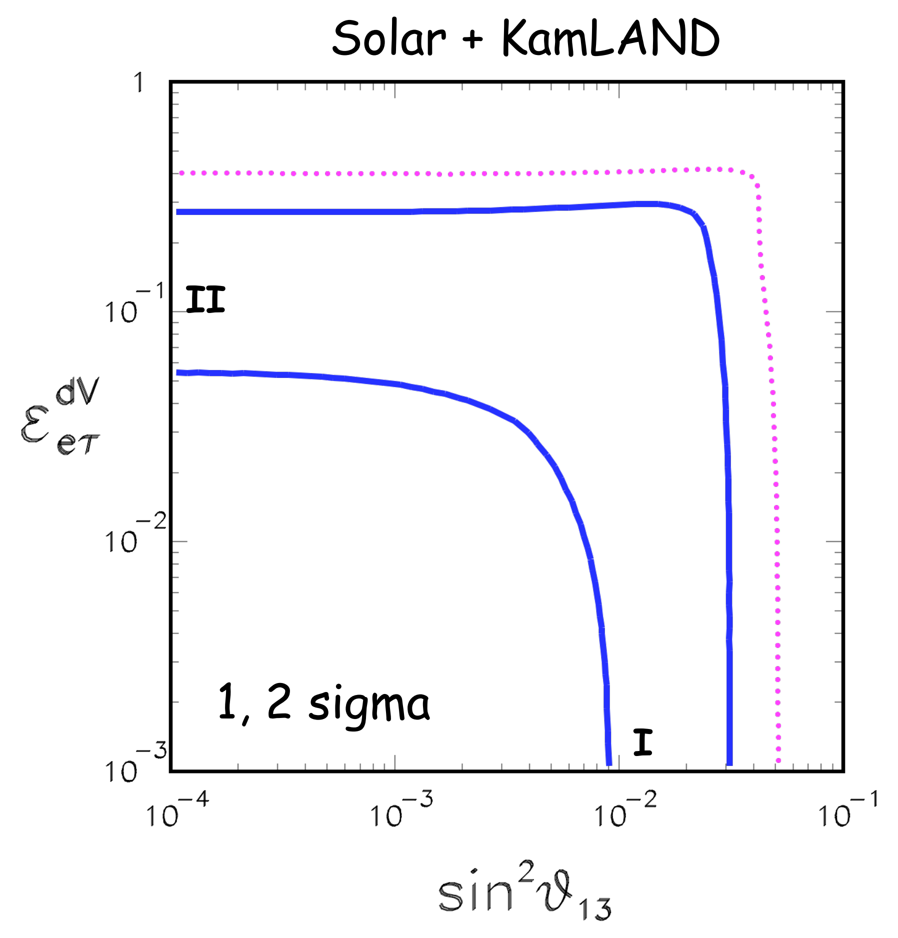
Sol+Kam combination prefers ε ~ 0.17

Note that such couplings are not incompatible with the existing bounds

Davidson et al. 2003, Biggio et al. 2009

Combining the two remedies

θ_{13}-NSI degeneracy



A.P. and J.W.F. Valle, PRD 80, 091301 (R) (2009), arXiv:0909.1535 [hep-ph]

The goodness of the global fit (S+K) is ~ identical for the two limit cases:

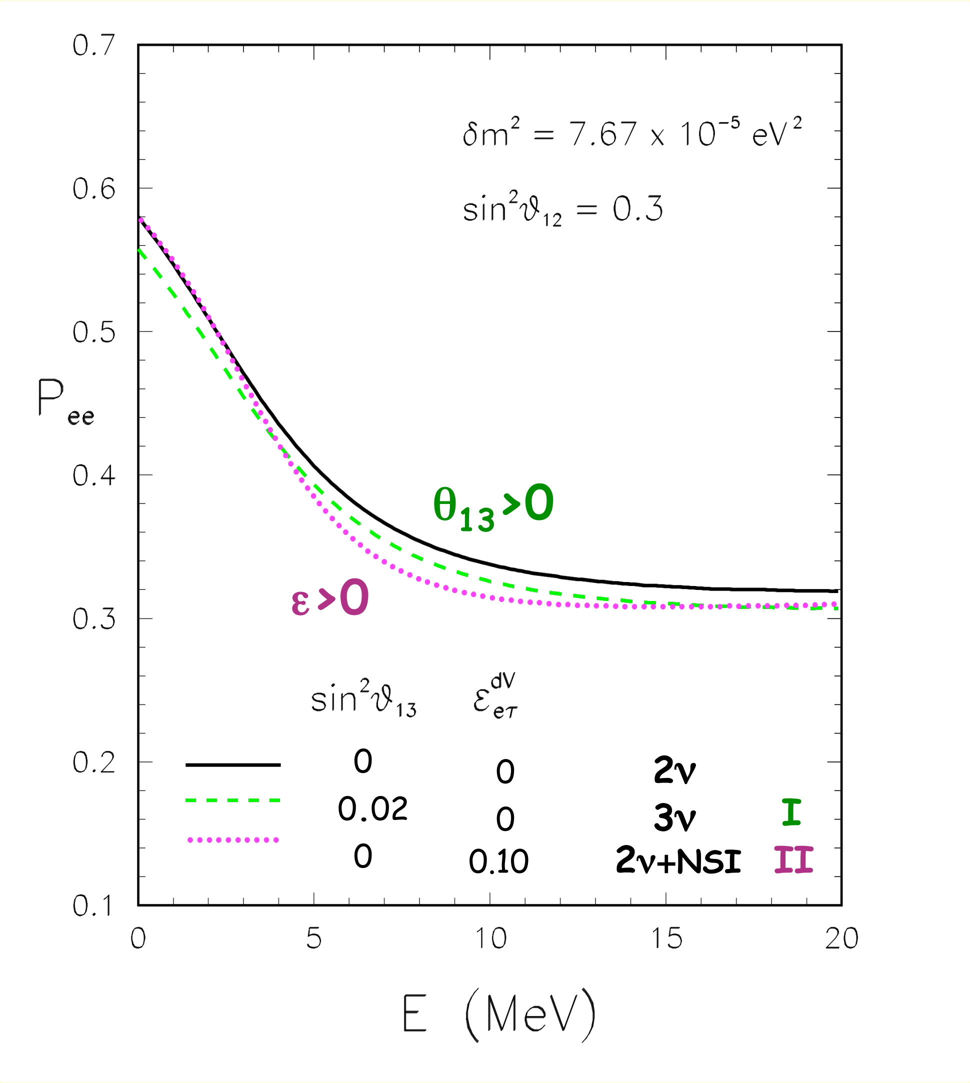
I) [$\theta_{13} > 0 \quad \varepsilon = 0$] (3ν)

II) [$\theta_{13} = 0 \quad \varepsilon > 0$] (2ν + NSI)

Full degeneracy between θ_{13} and the NSI coupling

Tension between Sol & Kam is shared among θ_{13} and ε

Can we disentangle the two effects?



A.P. and J.W.F. Valle, PRD 80, 091301 (R) (2009), arXiv:0909.1535 [hep-ph]

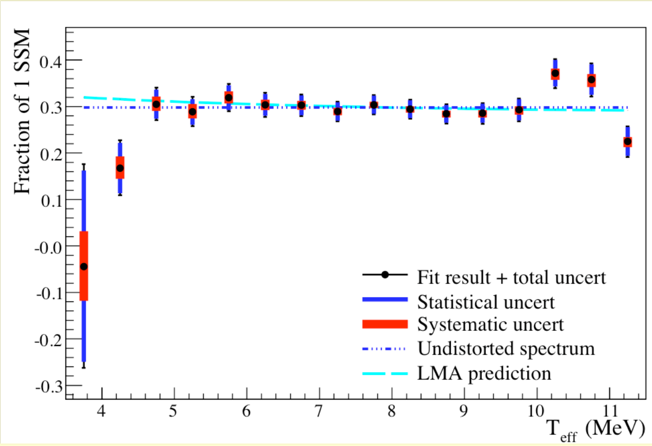
Small differences at
low energies (~3%)
may be hard to detect

At intermediate energies,
differences more pronounced:
Pee profile is flatter with NSI

Lowered threshold
high energy experiments
[SK-III, Borexino (^{8}B), SNO(LETA)]
might give
important information…

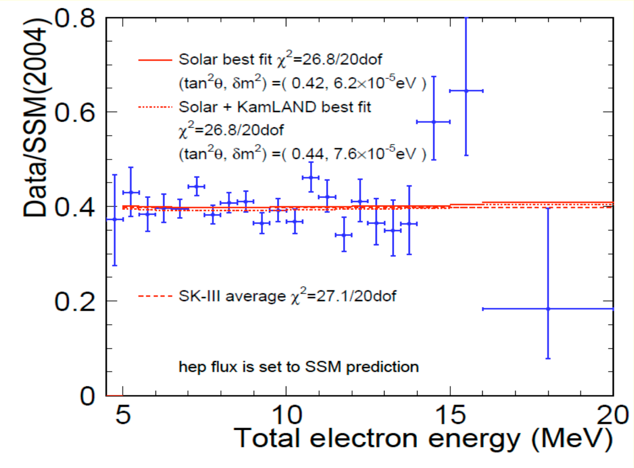
SNO LETA

PRC 81, 055504 (2010)



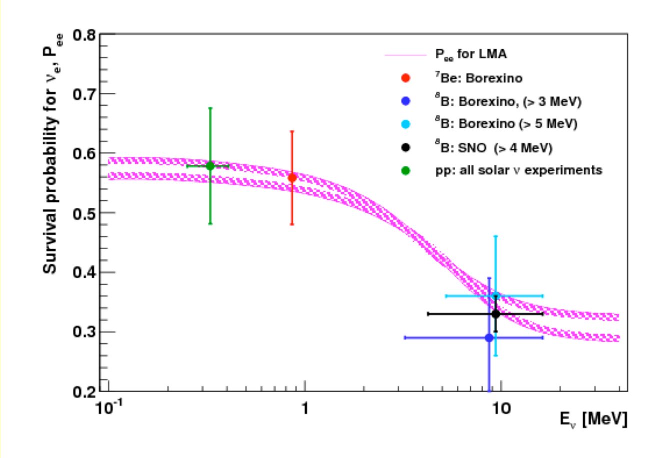
SK-III

(M. Ikeda @ NOW 2010)



BOREXINO

(M. Pallavicini @ NOW 2010)



No upturn visible !

Data tend to prefer NSI over θ_{13}

Conclusions

- A tension is present in the solar sector data. Although small it has a clear origin.

- The simplest remedy is provided by non-zero θ_{13} but NSI offer an interesting alternative.

- The first solar ν measurements in the "invisible region" at intermediate energies seem to favor NSI over θ_{13} but more data and new experiments are needed.

- The new reactor experiments will provide a "clean" measure of θ_{13} (unaffected by NSI). In case of a null result, a persisting S-K tension will strengthen the NSI hypothesis.

[redacted]

Back-up slides

Result established by CHOOZ in 1998

$$P_{ee}^{\text{osc}} = 1 - 4U_{e3}^2(1 - U_{e3}^2)\sin^2\left(\frac{\Delta m^2}{4E}L\right)$$

$P_{ee}^{\text{exp}} \simeq 1$ $U_{e3}^2 = \sin^2\theta_{13}$

(~ 4% error)

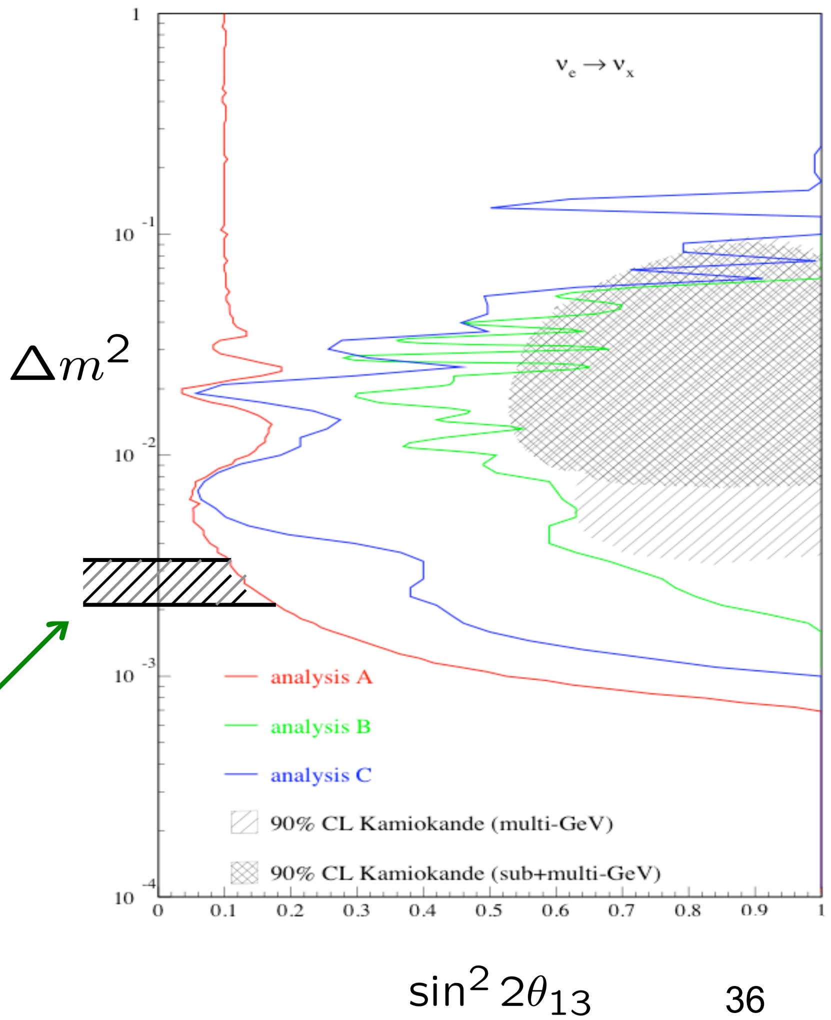
↓

Exclusion plot in the
$(\Delta m^2, \theta_{13})$
plane

Δm^2 scale (now)
set with precision by

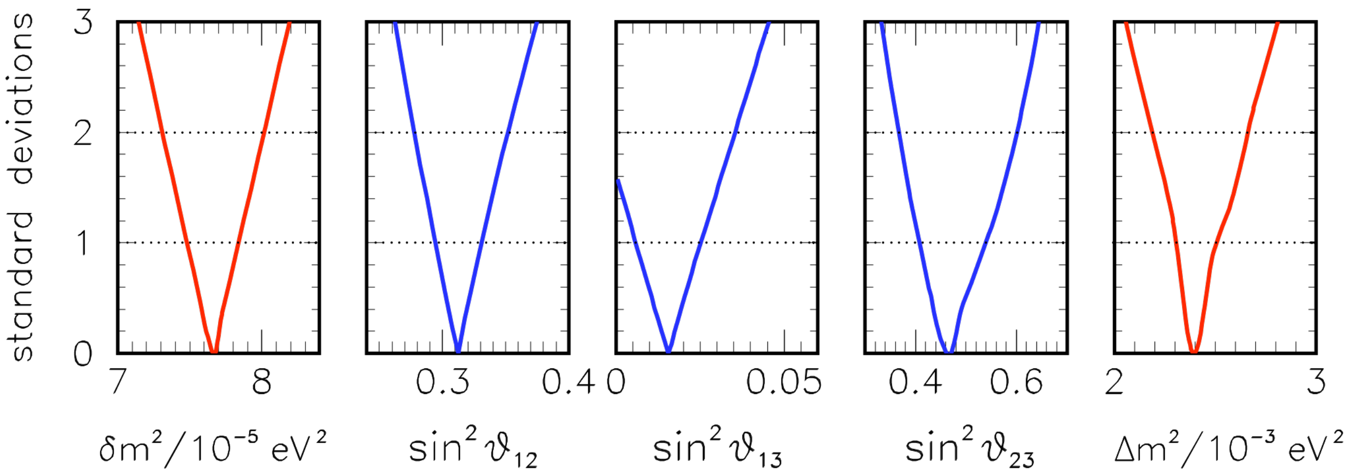
Atm
+LBL

CHOOZ exclusion plot



Global 3ν analysis

Fogli et. al. [PRD 78, 033010 (2008)]



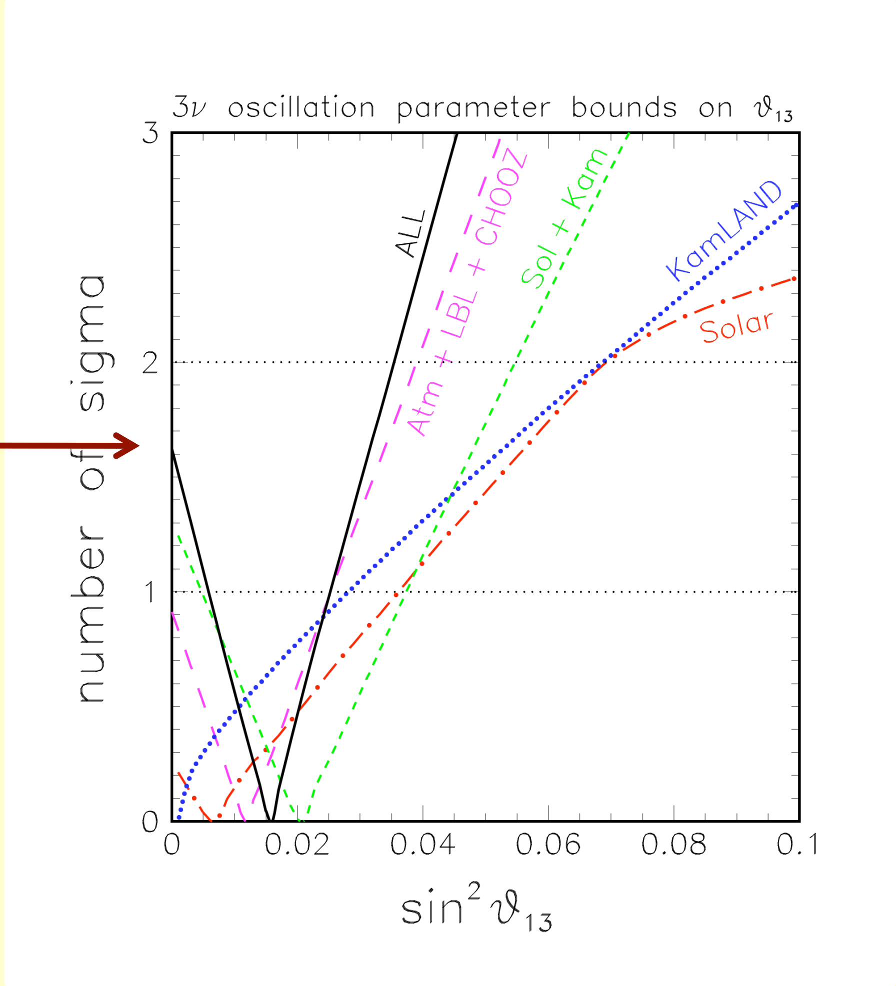
High precision on both mass splittings, now determined by "artificial" neutrino sources experiments (KamLAND for δm^2, MINOS for Δm^2).

Estimates of the two leading mixing angles is less accurate (especially θ_{23}), and experiments using "natural" ν's play a crucial role in their determination.

A preference for $\theta_{13} > 0$ at a non-negligible C.L (90%) emerged in 2008
Fogli, Lisi, Marrone, A.P, Rotunnno,
PRL 101, 141801 (2008), arXiv:0806.2649,hep-ph.

Global combination (2008)

Combining the data from the two sectors an overall preference for $\theta_{13}>0$ emerges at the 1.6 sigma (90% CL)



Current status of θ_{13}

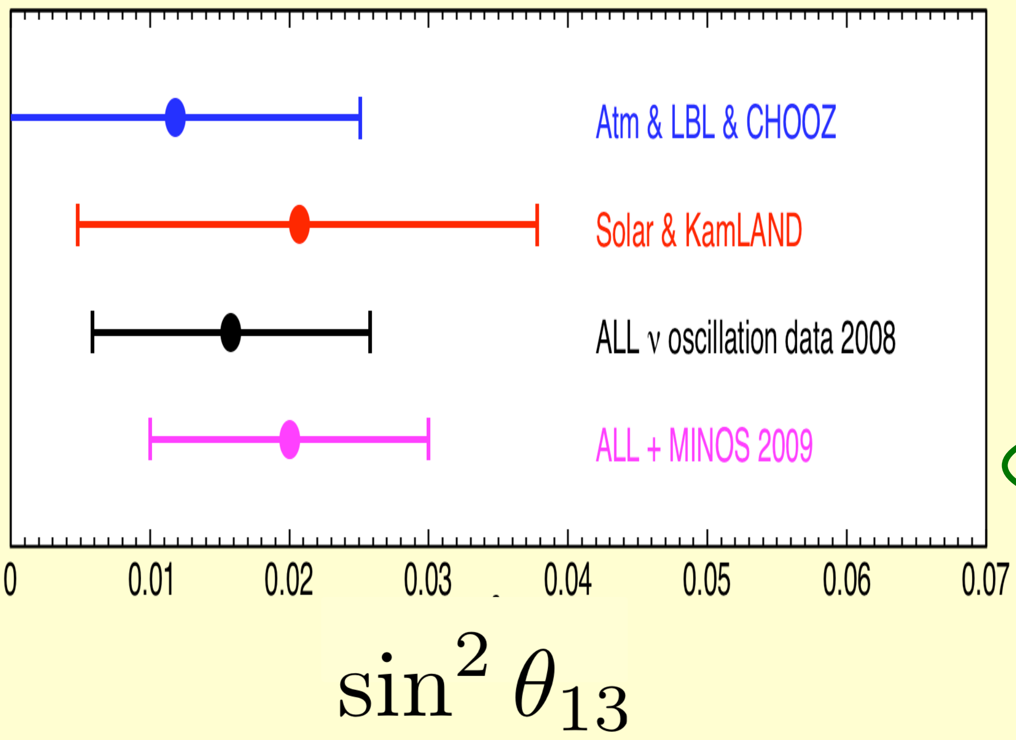
Hint

$0.9\ \sigma$

$1.2\ \sigma$

$1.6\ \sigma$

$\sim 2\ \sigma$



1σ range

0.012 ± 0.013

0.021 ± 0.017

0.016 ± 0.010

$\boxed{\mathbf{0.02 \pm 0.01}}$

SK and SNO response functions

Villante et al., Phys. Rev. D 59, 013006 (1999)

Both in SK and SNO the original energy info is **degraded**:

$$E_\nu \xrightarrow{\text{int.}} E_e' \xrightarrow{\text{det.}} E_e$$

$$\begin{aligned}
\rho_B^e(E_\nu,\, [E_e^{\rm min},\, E_e^{\rm max}]) &= \text{SK } (\nu_e,\, e) \text{ ES} \\
\rho_B^a(E_\nu,\, [E_e^{\rm min},\, E_e^{\rm max}]) &= \text{SK } (\nu_a,\, e) \text{ ES} \quad (a=\mu,\tau) \\
\rho_B^c(E_\nu,\, [\tilde{E}_e^{\rm min},\, \tilde{E}_e^{\rm max}]) &= \text{SNO } (\nu_e,\, d) \text{ CC}
\end{aligned}$$

The response functions describe **quantitatively** such “energy flow”

$$\rho_B^e = \frac{\lambda_B(E_\nu)\displaystyle\int_{E_e^{\rm min}}^{E_e^{\rm max}} dE_e \int_0^{E_\nu} dE_e' \,\frac{d\sigma^e(E_\nu,\, E_e')}{dE_e'}\, R_{\rm SK}(E_e,\, E_e')}{\sigma_B^e[E_e^{\rm min},\, E_e^{\rm max}]}\,,$$

$$\rho_B^a = \frac{\lambda_B(E_\nu)\displaystyle\int_{E_e^{\rm min}}^{E_e^{\rm max}} dE_e \int_0^{E_\nu} dE_e' \,\frac{d\sigma^a(E_\nu,\, E_e')}{dE_e'}\, R_{\rm SK}(E_e,\, E_e')}{\sigma_B^a[E_e^{\rm min},\, E_e^{\rm max}]}\,,$$

$$\rho_B^c = \frac{\lambda_B(E_\nu)\displaystyle\int_{\tilde{E}_e^{\rm min}}^{\tilde{E}_e^{\rm max}} d\tilde{E}_e \int_0^{E_\nu} d\tilde{E}_e' \,\frac{d\sigma^c(\tilde{E}_\nu,\, \tilde{E}_e')}{d\tilde{E}_e'}\, R_{\rm SNO}(\tilde{E}_e,\, \tilde{E}_e')}{\sigma_B^c[\tilde{E}_e^{\rm min},\, \tilde{E}_e^{\rm max}]}$$

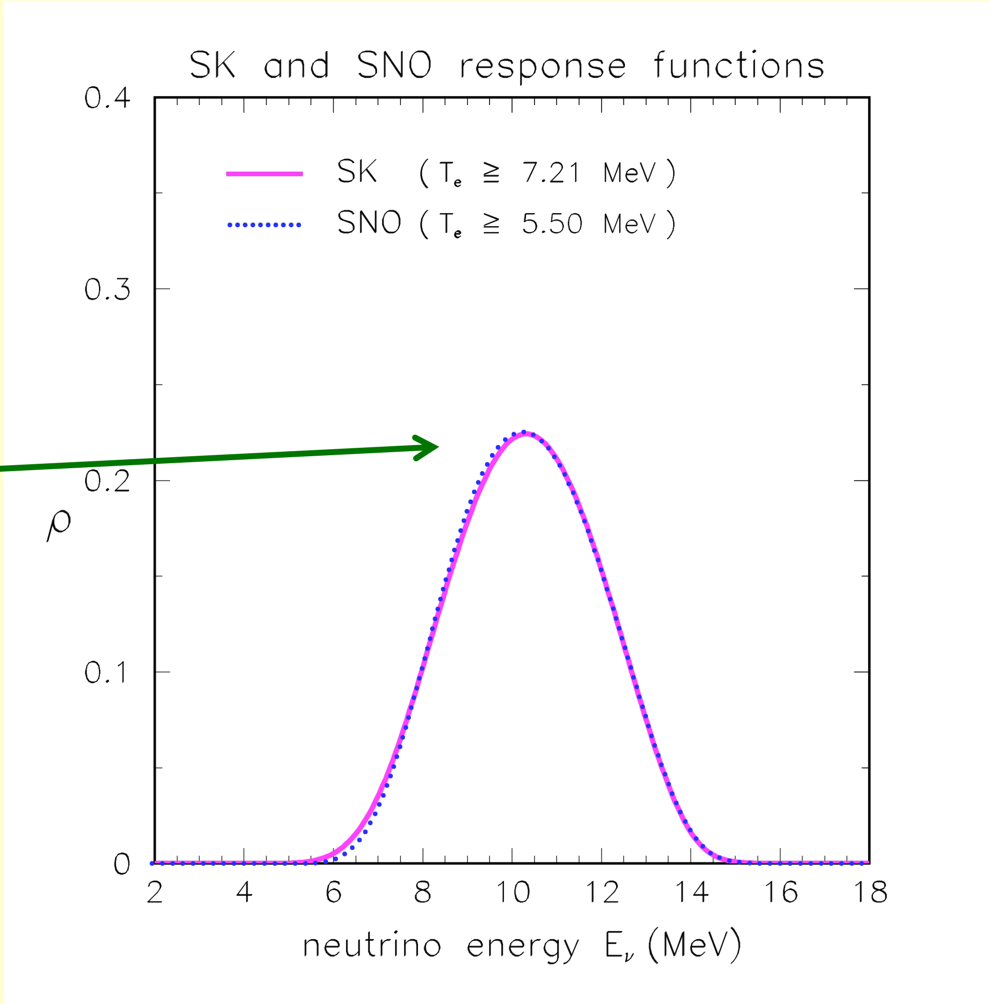
They represent the “**detected**” ν energy spectrum which is different from the original one

electron energy window

"Equalized" SK and SNO response functions

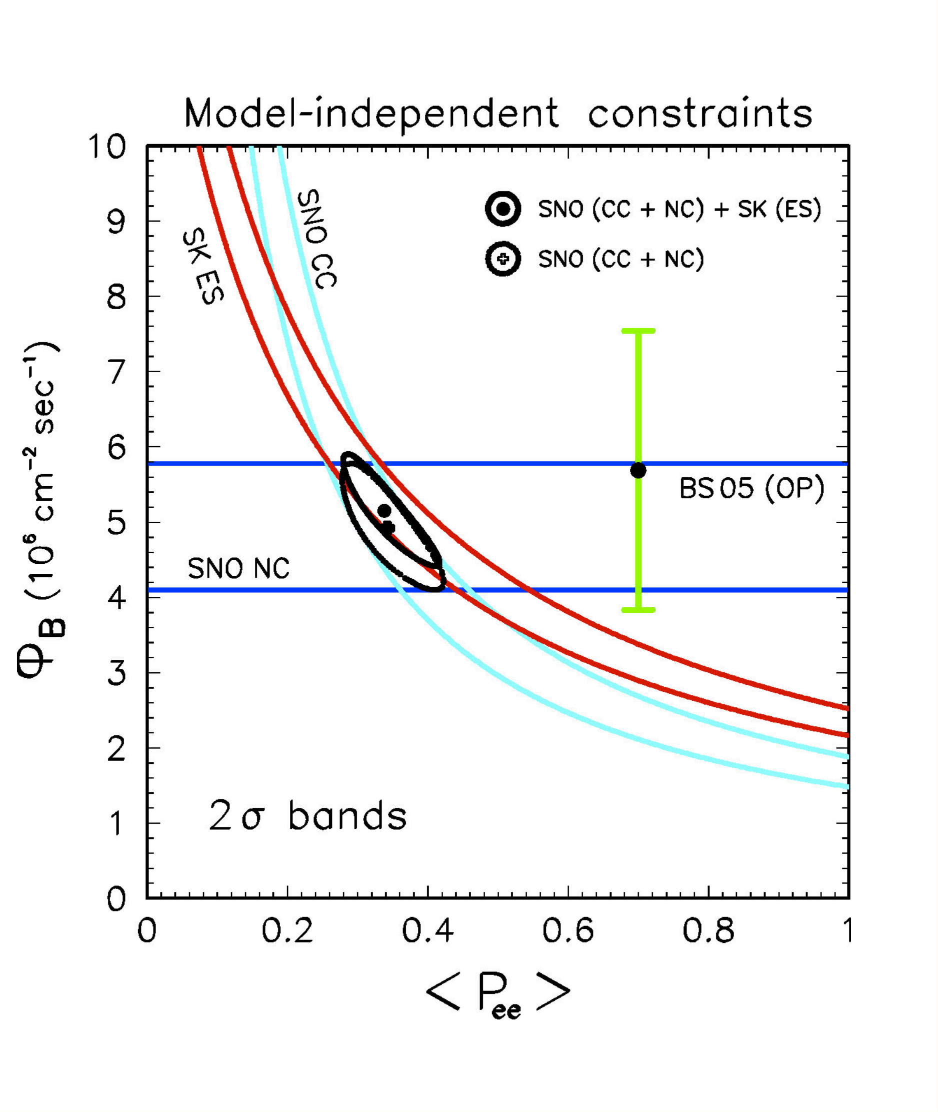
For **equal** energy windows
SNO (CC) & SK(ES)
resp. func. are **different**
(mainly due the different
cross sections)

However they can be
"**equalized**" with an
(appropriate) choice
of two different energy
windows



This "equalization"
allows us to compare
SK and SNO results in a
quantitative
model-independent way…

Model-Independent analysis



$$\begin{aligned}\Phi^{\rm SK}_{\rm ES} &= \Phi_B[\langle P_{ee}\rangle + r_\sigma(1-\langle P_{ee}\rangle)]\\ \Phi^{\rm SNO}_{\rm CC} &= \Phi_B\langle P_{ee}\rangle\\ \Phi^{\rm SNO}_{\rm NC} &= \Phi_B\end{aligned}$$

$\langle P_{ee}\rangle$ = energy-averaged **Pee**

$r_\sigma = \sigma_{\mu,\tau}/\sigma_e \simeq 0.154$

Internal consistency:
agreement with SK (ES)

Consistency with solar model:
NC in agreement with Φ_B